

The Spacing of Fracture Systems and its Influence on the Relief of the Land

by

Dr. Irving D. Scott

A thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in the
University of Michigan

Leipzig and Berlin
Wilhelm Engelmann
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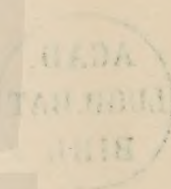
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VI.

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By

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With 12 figures in the text and plates I and II.

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Introduction.

Classification and Characteristics of Fractures.

One of the most striking characteristics of consolidated rocks of all kinds and ages, from the most ancient to the recent, is the presence of divisional planes. These planes are limited to the outer zone of the lithosphere and probably do not extend to a depth greater than eleven miles, since at this depth the rocks would be crushed by the weight of the superincumbent rock, making openings impossible.

The simple fractures in the rocks are commonly called joints and are classified by Van Hise according to the forces which caused them into tension and compression joints. Tension joints are generally small, almost vertical cracks with more or less irregular and curved faces, excepting those formed within folds. The tension is due either to shrinkage by cooling or desiccation, or by the bending of rocks into great folds. Shrinkage due to cooling is active in lavas after consolidation and results in prismatic or columnar jointing. Shrinkage as a result of desiccation occurs in fine sediments which are exposed to the air before consolidation, giving mud cracks, and is limited to local areas such as tidal flats, lagoons, valley flats, and intermittent lakes. Tension attendant on folding occurs on the convex sides of folds and forms radial cracks of great extent running parallel to the trend of the folds.

Compression Joints. The joints discussed above are of relatively minor importance and it is the compression joints that we wish to consider more in detail. In contrast to tension joints, compression joints are almost universal in distribution, more numerous, more extensive, more perfect in development, and have an importance in other respects that so far outreaches fractures by tension that the term joint is commonly understood to refer to those of this type.

In general, we may say that joints are divisional planes in rocks which have more or less smooth plane surfaces, which stand in a nearly vertical position, and have not undergone any differential movements of the walls. They vary in length, depth, azimuth, number, spacing, character of the plane of separation, and in the amount of separation between the walls, called gaping. The length and depth of joints vary from short cracks of a few inches in length

which extend downward through one bed only, to fissures of great extension which cut through beds to the lower limit of observation.

The surface of separation is often a very close approximation to a plane surface and appears as though cut with an instrument, holding its course through variations in hardness of the rock, cutting through different kinds of rock, and even dividing the pebbles of conglomerates into cleanly cut parts. Not infrequently it is subject to various irregularities. It may curve and so change direction, follow a slightly serpentine course, or be broken by minor irregularities known as feather fracture, border planes, and deviations which appear to be without system. Aside from the variations in the plane of separation which may change the direction of a joint, all azimuths may be found. The amount of separation is a variable quantity and gaps are found of from three to four inches down to widths so narrow that a thin piece of paper cannot be inserted. The larger values are exceptional and are probably due to weathering.

The relation of the joint plane to verticality is subject to small variations except in a few cases where they have been found inclined about 45° to the horizontal. The number of joints, or, from the other viewpoint, the space interval between the joints, is subject to wide variation both in the same rock and in different rocks. Thus, according to the kind of rock, the interval is greatest in sandstone, decreases in limestone, and is least in shale; and in any given kind or even in the same bed of rock it is not constant.

The variations enumerated above may all be present in a given locality within the same rock as well as in different kinds of rock, e.g., joints within the same layer of rock are subject to the same variations as those in a bed of different kind of rock, but the variations are not necessarily of the same order of magnitude; while, if several localities are considered, it does not follow that the joints in the same type of rock will be identical, e.g., the Tully limestone in the Ithaca region shows great variations in its planes of separation, while the limestone in Schoharie County, N. Y., is divided by almost perfect planes which are more widely spaced than those of the Ithaca region.

Joint Systems. It is seen from the above that joints are subject to variations of many kinds and exhibit gradations within local areas and from district to district, but investigation has clearly shown that the variations are to some extent interdependent and that there is present, except in the most complex districts, a definite

grouping and arrangement of joints into systems which include the greater part, if not all, of the fractures of the region.

The most striking characteristic of joints is their tendency to divide the rocks into vertical prisms of rectangular outline which, in turn, may be subdivided by joints of inferior development (see plate Ia). This necessitates divisional planes of different orders of magnitude, a grouping of the joints into parallel series, and at least two series which intersect at nearly right angles, forming what is known as a set by some authors and a conjugate system by others. The well-developed joints which bound the prisms, the master joints, may extend for great distances, both vertically and horizontally, and usually gap more than those of minor development which run parallel and divide the interval between them.

It is not to be understood that the general statement concerning parallelism holds for all areas and all joints within an area. In some cases, as in Schoharie County, N. Y., all of the joints are included in two series which intersect at 107° , giving complete parallelism, but in some regions, a complex maze of intersecting fissures confronts one. Such exceptions are in some instances more apparent than real, for careful measurement usually shows a large percentage of the joints grouped under two predominant directions and the parallel series thus shown intersect at nearly right angles.

In local areas a single series only may be found, but the usual occurrence is such that one or more sets is present. Where the system is composed of two or more sets, one usually predominates and there is a tendency for the second set to run along the diagonals of the blocks formed by the predominant set. The direction of the diagonal set is subject to variation within the quadrant but mean values are usual.

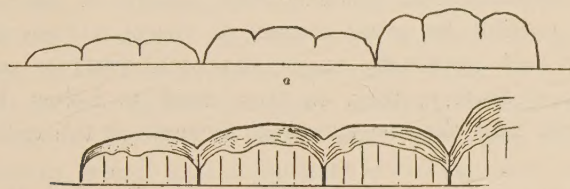
Spacing of Joints. In favorable areas the spacing of joints of at least two orders of magnitude within each series has been noted, e.g., in Norway, where vegetation and soil do not obscure the structure, this is shown by the notching of the crests caused by excessive weathering along joint planes. (Fig. 1.)

Considering now the prisms formed by the intersecting joints, there results a series of blocks, nearly uniform in size and shape, called unit blocks, and these blocks may be grouped to form composite blocks, similar in shape but larger and made up each of a definite number of unit blocks.

Relation to Faults. So far joints only have been discussed.

If differential movement has taken place along the fracture, it is by definition described as a fault. In many cases this differential movement is very difficult to ascertain, though the displacement may vary from thousands of feet to imperceptible amounts with all gradations. Therefore faults are considered genetically related to joints which were pre-existent in the rocks and hence offered lines of least resistance for differential movement. It does not necessarily follow that faults are always straight and parallel throughout, although they may be. When the line of displacement is not parallel to any joint

Fig. 1.



Diagrammatic profile to show interval relations of joints of different orders of magnitude within the same series, Norwegian Coast (after Hobbs).

direction, it may be accommodated along the two directions of a set of joints giving rise to a zig-zag escarpment whose trend may be either straight or curved and in any direction.

Influence of Fractures on Drainage.

Faults and joints are so closely related that it is necessary to class them together in considering the influence on drainage and topography, and the term fracture in the title and subsequent pages of this paper is designed to include both faults and joints. These lines of least resistance provide channels for the running water, the result of which is characteristic orientation or, in the case of fault scarps, it may be shown in waterfalls and in ponding into lakes. Where the drainage is underground, fractures supply ready-made channels through which the water flows both in its downward and its lateral movements. The solvent action of the water during its passage forms cavities within the rocks, the larger of which are known as caves or caverns and consist mainly of interlacing stream channels whose peculiar orientation shows a resemblance to joint systems that is too striking to be accidental.

The control of drainage by fractures is, however, not limited to underground water but is manifested as well on the surface. This

is especially true of regions where the mechanical processes of weathering are predominant and the structure is not buried beneath a mat of vegetation, but it is not limited to them. Such regions are those in which the solvent action of water, or the mechanical work of frost, waves, or wind is the dominant eroding process. The master joints are obviously the more important in this connection, their narrow cracks being lines of least resistance for the action of the weathering processes. The incipient rill, whose course is easily influenced by minute differences in relief, finds these widened fractures and develops longitudinally, laterally, and vertically. Once a stream course is established, it remains fixed, except in case of accident, hence it is possible for great streams to reveal in their direction the influence of such apparently minor structural features as fractures. As tributaries develop, they, in turn, tend to follow the fractures whose control may thus be exercised throughout the entire drainage system.

Whether or not a stream follows one direction for any great distance depends on the relation of the initial slope to the fracture system. If the slope runs parallel to the joint direction, the streams naturally follow the joints and are rectilinear in character, but, if the slope is not parallel to a joint direction, the streams proceed down the slope in a series of zig-zags whose sides may have relatively different values. In the case of faults of appreciable throw, such control is much increased.

Where streams are actively deepening their channels, control may be indicated through the observed correspondence in direction between fractures and stream channels, but as erosion proceeds fault scarps are reduced and joints are obscured by the accumulation of a mantle of soil and vegetation and by deposition in the stream beds, making direct observation impossible. Under such circumstances, another method of determining the existence of control may be resorted to. This consists in a comparison of the characteristics of streams of known fracture control with the stream in question. These characteristics are: 1. straight valleys which may pass across various kinds of rock and along which streams may flow even in opposite directions; 2. parallel courses in various parts of the same stream or in different streams; 3. "elbow bends" which are rectangular in character; 4. the ends of minor tributaries which all bend in the same direction; 5. the opposite junction of tributaries with the main stream extended upon the same straight line; 6. the rectangular branching

of tributaries; 7. the very striking characteristic which streams controlled by fractures possess of returning persistently to the original straight course after deviation from it.

The contrast of streams possessing these characteristics with a "normal" stream whose drainage network resembles the branching of a deciduous tree is so striking as generally to permit of a definite conclusion concerning the measure of control that has been exercised by the fracture system.

Influence of Fractures on Topography.

The influence of fractures on weathering and drainage must necessarily leave its stamp upon the relief forms of a region so controlled. Some of the details are zig-zag walls, either in stream gorges or sea cliffs, isolated pillars of angular outline, sea arches and stacks, coves and inglenooks. On a larger scale are found characteristic angular patterns which repeat themselves. They may cover great areas and often change direction abruptly to correspond to changes in the fracture system. Examples of such patterns are "checker-board topography", due to erosion about the blocks of the larger orders within a fracture system. When the blocks stand at notably different levels as a result of faulting, this has been referred to as a "floating block topography".

Considerable work has been done on the problem of fracture systems and the control of drainage which results from their influence, but there is much remaining to be done. The systems have been described and correlated as far as the data will allow and there are indications of a world fracture system composed of a meridional set with fractures trending N-S, and E-W and a diagonal set running NE-SW and NW-SE, but the observations are far from complete. Some attention has been given to the influence of fractures upon relief, but not enough has as yet been done to determine its relative importance compared with other possible influences. The spacing of joints has had some attention but mostly in the line of general observations. The writer has found only three investigators who have recorded measurements and these are few. Equal or approximately equal spacing has been noted in a few localities and multiple or sub-equal spacing in two regions, but it remains to be shown how general this is. The spacing varies in different kinds of rock, but, as yet, no cause has been shown.

Author's Investigations.

It was with these unsolved points in mind that the author undertook as comprehensive a study of the problem as was possible under the circumstances, but with the definite question of the spacing foremost; and it is chiefly with this topic that this dissertation is concerned. The methods of attack were two, field observations and map study. The field work was done in three localities, — central Illinois, Schoharie County, N.Y., and the Cayuga-Seneca lake region of central New York. The localities were chosen because of the perfection and simplicity of the joint systems and on the general principle of starting with the simple to avoid the confusing details of the complex, and proceeding to the complex later. The Illinois district proved unfortunate in that the joints were complex and far from well developed, but the districts in New York were well suited for the investigation.

From the map study it was hoped to establish characteristic junction angles of streams whose courses are controlled by slope alone and by fractures. With such means at our command it would be possible to select maps which show fracture control without a detailed field study. Up to the present it has not been possible to determine to what extent each of these factors has controlled, hence this part of the investigation is not included.

The study of maps of regions of observed faults was productive of better results which appear with those of the field observations in the general conclusions of the paper.

The writer wishes to express his thanks to Professor W. H. Hobbs of the University of Michigan for many valuable suggestions, friendly criticism and interest during the progress of the work, to Mr. Charles G. Brown of Ithaca, N.Y. for the use of unpublished data, and to Dr. E. C. Case of the University of Michigan for kindly placing at his disposal unpublished data concerning the faulting of the Gallina district in New Mexico.

Historical Résumé.

Pioneers.

The earliest work on fractures was an accompaniment of the mining industry that developed in southern Germany soon after the Renaissance. The mineral veins were all important in this work and, consequently, were studied in detail.

Agricola¹⁾ (Georg Bauer) in the early 16th century believed that veins are fissures which have since been filled with mineral matter. Linnaeus²⁾ about a century and a half later studied the veins and concluded that the fissures from which they were formed were due to contraction from desiccation. Soon after Dr. Pryce²⁾ in his *Mineralogia Cornubiensis*, 1778, expressed the same opinion as Linnaeus as a result of his studies in the Cornwall mining district.

About this time Werner in Saxony was exerting a profound influence on geology, and in his last contribution, "The New Theory of Mineral Veins", he established conclusively that veins are filled fissures and commented on the origin of the fissures. He admitted that there are various causes, but assigned most of them to subsidence. This subsidence was due to sinking and drying of sediment, which first was soft and movable, and caused fissures, chiefly in regions where mountain chains and high land existed.

Early Observational Period.

With De Saussure began a period which may be called truly observational. This great nature lover was a firm advocate of exact observation, exhibited freedom from bias, and exercised caution in forming conclusions. In his work *Voyages aux Alpes* (Vol. III), he describes fissures and speaks of the rocks as cut into blocks by planes so constant that the pebbles of conglomerates were cut as by a razor. This fact was also noted by Hutton³⁾ who was puzzled by it. In his opinion the fissures must have been the consequence of an immense impulse very suddenly communicated to the rocks when they were upheaved.

In 1811, Berger⁴⁾ noted the existence of regular equidistant fissures which appeared as though cut with a chisel and divided the rock into horizontal masses similar to basaltic columns. He believed that the fissures, although regular in form, were accidental splittings. In the writings of Sedgwick⁵⁾ fissures are described as preserving an exact parallelism among themselves for a considerable distance,

¹⁾ Taylor, John, Report on Mineral Veins. Rept. British Ass'n, III, 1834, pp. 1-25.

²⁾ Taylor, John, loc. cit.

³⁾ Playfair, John, The Huttonian Theory. 1802, pp. 207-8.

⁴⁾ Berger, J. F., Trans. Geol. Soc. London, I, p. 151.

⁵⁾ Sedgwick, Adam, Cambridge Phil. Trans., I, 1820, pp. 96-146 and 303.

and, not infrequently, were cut by a second series nearly at right angles to the former, in consequence of which the whole aggregate was separated into blocks of rhomboidal form. He noted directions running parallel to the strike and dip. His conjecture as to the cause was a crystalline arrangement of the whole mass around different centers.

Later, Hopkins¹⁾ worked on the cause of fissures and advocated tension due to elevation. He accepted Sedgwick's dip and strike joints and attempted to show mathematically that fracture would take place perpendicularly to the direction of tension, and that any other system subsequently formed must be perpendicular to the first. Sedgwick²⁾ later accepted this view in a paper read before the Geological Society of London.

The name of John Phillips³⁾ is an important one in the history of our subject, for he appears to have been the first to make a comprehensive and systematic study of the fracture problem, and give measurements of directions. He defined a joint as an apparent divisional plane which is not coincident with stratification and gave many characteristics which were additions to the knowledge of the subject. He stated that joints traverse all rocks but vary in number, regularity, and direction; and that there is a peculiar character of jointing for each type of rock. The number is greatest in shale and decreases in limestone, sandstone, and conglomerate in the order given. To those more dominant, regular, and uniform in direction he gave the name master joints and showed that these would be the lines of least resistance for the differential movements which produce faults. He regarded joints as an essential and necessary part of the structure of rocks and not as accidents. The constancy of direction, he claimed, shows the action of a very general cause of formation which, if not crystallization, is to be considered as a symmetrical aggregation of the molecules.

Immediately following Phillips's first paper Austen⁴⁾ described the joints of the Old Red Sandstone in Devonshire, where again

¹⁾ Hopkins, W., *Trans. Cambridge Phil. Soc.*, VI, 1836, pp. 1—84.

²⁾ Sedgwick, Adam, *Trans. Geol. Soc. London. Ser. 2, III*, 1835, pp. 480—86.

³⁾ Phillips, John, *Illustrations of the Geology of Yorkshire*, London, 1836; *Rept. British Ass'n*, IV, 1834, pp. 654—657; *Manual of Geology*, Revised by Seeley. 1855.

⁴⁾ Austen, Robert, *Trans. Geol. Soc. London. Ser. 2, VI*, 1834, pp. 455—456.

were found the two intersecting series. He gave considerable attention to spacing and was the first to publish any measurements, but these were few in number and showed nothing of importance.

Subsequent to Austen, many observers in England and America, notably De la Beche¹⁾, Hitchcock²⁾, Mather³⁾, Jackson³⁾, Houghton³⁾, Silliman³⁾, Rogers³⁾, Jukes⁴⁾, and Murchison⁵⁾, became interested in joints and recorded observations, which brought out two predominant sets with minor ones cutting the principal sets at acute angles. Many forces were invoked in order to account for the manner of formation, among which were galvanism, crystallization, and tension either from uplift or shrinkage; but the observations led to no definite conclusions.

In the late fifties of the nineteenth century we find publications by three important investigators in this field, namely, King⁶⁾, Harkness⁷⁾, and Haughton⁸⁾. King and Harkness worked in Ireland, while Haughton made observations both in Ireland and in southwestern England. King found in general four distinct joint series present, one of which is more strongly developed than the others, and mentions intervals as close as 6—12 inches, although no measurements were given. He made an important advance in that he attempted to correlate his west meridional set with the predominant set in England. In his later paper he advocated that joints are formed perpendicular to bedding and, if in a position other than vertical, have been tilted; and that inclined joints were due to shearing in a horizontal plane.

The points of especial interest in Harkness' paper relate to inclined joints, to spacing, and to the effect of the character of the rock upon jointing. The inclined joints he found to occur on opposite sides of a local exposure and to dip in opposite directions

1) De la Beche, Henry, Geological Report on Cornwall etc. 1839; The Geological Observer, London. 1851.

2) Hitchcock, Edward, Final Rept. Geol. of Mass. 1841, pp. 418—419.

3) Mather, W., Jackson, C. T., Houghton, D., Silliman, B., Rogers, H. D., Am. Jour. Sci. XLI, 1841, pp. 172—3.

4) Jukes, J. Beete, Physical Geology, London, 1833.

5) Murchison, R. and Morris, Q. J. G. S. II, 1855, p. 423.

6) King, Wm., Trans. British Ass'n, 1858, pp. 83—84; Trans. Roy. Irish Soc. XXV, 1873, pp. 605—637.

7) Harkness, Robert, Q. J. G. S. XV, 1859, pp. 86—104.

8) Haughton, Samuel, Trans. Roy. Soc. London. CXLVIII, 1858, pp. 333—348; CLIV, 1864, pp. 393—412.

without crossing. This he ascribed to crystallization because the angles agreed with those of a rhomb of calcite, but he was at a loss to account for the similar occurrence in shale. The spacing he found to vary, but in one locality he described joints cutting the strata which stand on edge, in such a manner as to give them the appearance of vertical strata not more than six inches in thickness.

He referred the perfection of jointing to the mineral nature of the rock; and as proof gave analyses of a pure limestone and a siliceous limestone, and cited a case of more minute and perfect joints in fine shale than in arenaceous shale. However, he was not able to state why shale, which is of very complex mineral content, should be better jointed than limestone. He showed that joints were formed subsequent to consolidation and cleavage, but did not attempt to explain the manner of formation except in the case of inclined joints.

Haughton seems to have been influenced by Phillips's investigations and, in addition to a careful description of the joints, he gave measurements of their direction. He showed the presence of conjugate systems, or sets as they were called later, whose angle of intersection approximated 90° . In some cases as many as four conjugate systems were found, two of which, however, greatly predominated. In the five localities measured the conjugate systems could be roughly correlated, the variation in direction being as high as 18° . There is objection to his method in that he averaged the joints, but his conjugate systems seem none the less to have been well established. As to the cause of joints Haughton advocated a mechanical origin involving compression. Cleavage, he believed, was due to the flattening of particles and developed perpendicular to the lines of maximum force and jointing perpendicular to the lines of minimum force; therefore, it was concluded that joints are formed subsequently to cleavage and are due to tension.

Later Investigators.

Up to this time the investigations were limited to observations on the characteristics of joints, to their correlation, and to discussions concerning the cause, yet without convincing arguments or unanimity of opinion. The advent of accurate topographic maps opened up the new field of the influence of fractures upon the relief of the land and rapid progress was made. The pioneer in this line was

G. H. Kinahan¹⁾, a member of the Irish Geological Survey, whose position is clearly stated as follows: "But for the existence of faults, joints, and other shrinkage fissures, very few, if any, valleys could have acquired their present form". Those formed without their aid are due to synclinals but are of very small extent and rare occurrence. His ideas were decidedly extreme and based on evidence limited to Ireland, but the pendulum had swung so far towards simple sub-aerial denudation that a radical stand was necessary in order to receive any consideration. To him we are indebted for the idea that fractures are "lines of weakness and of shattered strata ready to be moved by the first denuding agent that may act upon them". He showed that river courses, both straight and tortuous, are oriented parallel to fracture systems, if not along them; and he believed that the presence of side valleys at sudden bends was evidence of a fracture, although this could not be proved. To him, the striking thing was that the trend lines of the topography of the island lie in a system whose components are roughly N-S and E-W, the former being the more prominent. This he claimed cannot be accidental and stated that fractures have actually been found in some of the valleys.

At the same time Kjerulf²⁾ was working independently on this same problem in southern and central Norway. He detected the presence of a system of fractures composed of two sets running N-S, E-W and NE-SW, NW-SE. He stated that these fractures rather than the difference in the hardness of the rocks paved the way for erosion and cut the land into blocks, some of which sank below sea level forming fjords, sounds, etc., while the position of others remained unchanged, forming the great angular mountain masses.

In France Daubrée³⁾ had been working on experimental problems in the geological field, and fractures formed an important part of these researches. His brilliant experiments on the cause of joints awakened wide-spread interest and led to a satisfactory solution of the problem. In brief, he showed by torsion on glass plates and by compression on a mixture of plaster of paris, beeswax and Florence varnish, that by either force all of the characteristics exhibited by

¹⁾ Kinahan, G. H., *Valleys and their Relation to Fractures, Fissures and Faults*. London, 1875.

²⁾ Kjerulf, Th., *Geology of Norway*. Translation by Gurlidt, 1880, p. 332.

³⁾ Daubrée, A., *Comptes Rendus*, LXXXVIII, 1877; LXXXIX, 1878; *Bull. Soc. Géol. de France*, Sér. 3, VIII, 1879; *Géologie Expérimentale*. Paris, 1879.

joints could be explained, though he leaned towards tension in the application of his experiments. His work was not limited to the laboratory, but included an immense amount of field observation and map study. The description of the characteristics of joints was mainly corroborative, having been pretty well covered by earlier writers, but great progress was made on the influence of fractures upon relief. The detailed features formed by fractures are given as scarps and fault valleys in the case of faults, and isolated rocks of parallelo-piped form in the case of joints. On a larger scale, he believed that faults and even joints influenced the courses of streams, and he called attention to the general design of regions thus influenced as shown on accurate topographic maps. The evidence to support this view is the rectilinear, parallel, and "elbow like" character of the stream courses, and the continuity of a single direction for different streams. By this method he showed fracture control in many areas in France, and, although he admitted that joints must gap to exert control, he considered this a much more important factor than was generally credited.

One of the first to comment on Daubrée's experiments was Green¹⁾ who accepted his conclusion that torsion and compression were each competent to form joints, but he considered that the nature of the material was also important. On the other hand, Goodchild²⁾ considered torsion impossible and assigned compression as the cause.

A short time later Brögger³⁾, with the studies of Daubrée and Kjerulf in mind, continued the work of the latter in the Christiana region, Norway. He accepted compression as a partial cause of the fractures and, from the directions of the principal ones (N 5°—10° W and E. N. E.), concluded that the direction of compression in this region was N 60° W. The faulting was caused by displacements along these joints due to gravity. The influence of the fractures on relief is stated by Brögger in the following translation: "the lines of landscape are given by the principal joint systems and the faults have cut the landscape through and through parallel to the various systems of joints". The result of this is that the crust of the earth is here "built up like separate blocks of masonry".

¹⁾ Green, A. H., *Physical Geology*. London, 1882.

²⁾ Goodchild, J. C., *Geol. Mag.* New Ser. X, 1883, pp. 397.

³⁾ Brögger, W. C., *Spaltenverwerfungen in der Gegend Langesund-Skien*, *Nyt Magazin for Naturvidensk.* XVIII, 1884, pp. 253—419; XXX, 1886, pp. 231, 996.

During this same period, interest in America was awakened by a short description by Gilbert¹⁾ of some very perfect joints in recent lake clays in the basin of Lake Bonneville, and later by Russell²⁾ in the Lahontan basin. The lively discussion that followed was entered into principally by LeConte³⁾, Gilbert⁴⁾, and Crosby⁵⁾, and resulted in a modification of Daubrée's torsional theory of the cause. Crosby repeated the experiments with torsion on glass, but with the modification that the glass was strained varying amounts below the point of rupture and a sudden shock applied causing fracture. The results were identical with Daubrée's and substantiated Crosby's idea that the rocks were under torsional strain which exceeded the point of rupture only when a sudden shock such as that of an earthquake was transmitted to the rock, and that the direction of the fractures was determined by the pre-existing strain. Crosby, however, did not limit his work to the cause of joints but gave some little attention to spacing. He found this variable, but in the Miocene clays in Westmoreland County, Va. noted a surprisingly constant interval. Fifty readings in groups of ten are given which vary between 8 and 15 inches with a value of 10—12 including 75 % of the readings. The joints at right angles to this varied little from a 2 foot interval, but measurements were impossible.

Crosby's theory, while received favorably by Gilbert, was not accepted in all respects and it remained for Becker⁶⁾, as a result of a study of the Sierra Nevada, to point out that joints due to tension (torsion) are apt to curve and have irregular surfaces, and should gap when first formed. On the other hand compression would cause smooth, clean faces in close contact, and this is the nature of joint faces in general. He then demonstrated mathematically that rupture in a homogeneous mass under compression must take place on the lines of maximum tangential strain, and that these lines would stand at 45° to the line of force, if the mass presented infinite resistance; and at greater angles if the resistance is not infinite. This holds when rupture is brought about by a not very rapid stress, but

1) Gilbert, G. K., *Am. Jour. Sci.* XXIII, Ser. 3, 1882, pp. 25—27.

2) Russell, I. C., *Monograph XI*, U. S. G. S., 1885.

3) Le Conte, Joseph, *Am. Jour. Sci.*, XXIII, 1882, pp. 233—234.

4) Gilbert, G. K., *ibid.* XXIV, 1882, pp. 50—53; XXVII, 1884, pp. 47—49.

5) Crosby, W. O., *Proc. Boston Soc. Nat. Hist.* XXII, 1882—1883, pp. 72—85; XXIII, 1884—1888, pp. 243—248; *Am. Geologist*, XII, 1893, pp. 368—75.

6) Becker, G. F., *Bull. Geol. Soc. Am.* IV, 1892, pp. 13—90; II, 1891, pp. 30—74; *Eng. and Mining Jour.* LXXIX, 1905, pp. 1182—1184.

where the stress is impulsive, the interference vibrations attending rupture may cause further parallel fractures. This theory, which accounts for the phenomena of joints and includes Crosby's idea of a sudden impulse, though relying entirely on compression, would appear to be the more generally accepted one at the present time. Becker also noted variable intervals between the joint planes and showed mathematically that the interval was related to the thickness of the bed, though he did not demonstrate this by observation. He found displacements along joints of all magnitudes and considered that the distinction between faults and joints has arisen because throws of small amounts have been so generally overlooked.

In 1895 Van Hise¹⁾ referred the origin of the Dells of the Wisconsin river to joint control and gave the following reasons: rectangular intersections, tributaries join trunk along joints, and the dells start as canyons twelve to fifteen feet deep at cols which are located on joints.

In New York State fractures have been given attention by Kemp²⁾ and Cushing³⁾. The latter described joints and faults in several localities and in Clinton County was able to detect faults of three orders corresponding to master and minor joints of different orders. Kemp was greatly impressed with the regular pattern of the relief in Essex County and his conclusions are best expressed in his own words, "one cannot resist the conviction when viewing the dome-shaped peaks or knobs, that they are in a large part due to block faulting". He gives as evidence of the faulting crushed or shear zones, ridges steeper on the eastern face and gently inclined on the western, and that ore bodies are often lost under gulches and small valleys. This conviction was strengthened with experience, as the following statement shows: "one is even justified in regarding each topographic depression as not only the possible but probable location of one" (fault).

In 1901 there appeared a paper by Hobbs⁴⁾ in which he showed that the Pomperaug Valley, Connecticut, region is cut into a mosaic

¹⁾ Van Hise, C. R., Trans. Wis. Acad. Sci. X, 1895, pp. 556—560.

²⁾ Kemp, J. F., N. Y. State Mus. Bull. III, No. 14, 1895; *ibid.* 47th Ann. Rept. 1894, pp. 627—666; *ibid.* Bull. 138, 1910, p. 79.

³⁾ Cushing, H. P., Bull. Geol. Soc. Am. VI, 1895, pp. 285—296; N. Y. State Mus. 49th Ann. Rept. II, 1895, pp. 499—573; *ibid.* Bull. 77 Geol. 6, 1905.

⁴⁾ Hobbs, W. H., Newark System of the Pomperaug Valley, Connecticut. 21st Ann. Rept. U. S. G. S. Part 3, 1901, pp. 1—162.

of orographic blocks by a system of faults consisting mainly of five series. The interval between faults of the same order of magnitude is either approximately uniform or a multiple of the usual distance, thus making the orographic blocks similar in shape and of about the same size, or else a multiple of this block. The blocks are essentially rhomboidal prisms approaching rectangularity, although polygonal blocks are present. The smallest that could be conveniently examined was termed a "unit block" whose dimensions are about 300 by 150 feet. Evidence that the unit blocks are divided into smaller blocks, and were grouped into composite blocks was also found. There is a tendency for the blocks to be upthrown in alternate order. He also pointed out that the faults grade into joints, as was shown by Becker a few years previous.

The effect of this structure on the drainage is seen in the characteristic stream channels which are like artificial canals of nearly level floor and of uniform width and straight margins from which the banks rise and which in many cases coincide in position with described faults; the zig-zag bends of the streams which are more regular than meanders; and in the harmony of direction of streams with the fault system, in many instances the faults being in immediate proximity to the stream.

There is evidence that this same control is present in the surrounding districts because the faults by extending into the crystalline rocks which surround the area determine the peculiar drainage network. The peculiarities pointed out are: a directing influence along two or more rectilinear directions, indication of a simple network along two sets of parallel intersecting lines, ends of minor tributaries all turn in a single direction, one tributary meets the trunk stream at an obtuse angle opposite a tributary meeting in normal position (acute), branching of tributaries at right angles to the stem, return of tributaries of different branches along the same straight line.

The topographic forms resulting from a rectilinear set of fractures were described as "checkerboard topography" when the surface is cut into squares of approximately equal size, which stand at about the same level. Other characteristic forms are the "floating block" type or the basin range structure of Gilbert, rampart slopes due to the distribution of throw over several faults, and "inglenooks" which are recesses of an escarpment due to the downthrowing of an orographic block. The latter approach a prismatic form, have steep

walls and nearly level floors, and often are without streams. In a later paper, Hobbs¹⁾ extended this work to the surrounding region and concluded that the rivers of Connecticut seem to show by the orientation of their channels the existence of a regular network of intersecting series of parallel lines which correspond closely in direction with the faults of the Pomperaug Valley.

In 1904 Iddings²⁾ demonstrated fracture control for the region north of Yellowstone Park and among his reasons we find especial emphasis given to the traversing by streams of different kinds of rock without deviation. In this same year Hobbs³⁾ introduced the term lineament for rectilinear earth features due to fractures. Such lines are shown by crests of ridges or boundaries of elevated masses, drainage lines, coast lines, and boundaries of geologic formations. He argued that, since there is essentially one system of control in the river system of Connecticut, and this corresponds in direction to the fractures of the smaller Newark area of the Pomperaug Valley, the faulting is regional rather than local. This regional faulting is expressed in the topography of the Atlantic border by a system in that the lineaments are comprised in spaced parallel series among which certain ones predominate. He stated that the evidence, although insufficient, strongly favors the view that the master fractures are not without relations to each other throughout large areas, and, since fractures are subsequent to folds, they are more likely to influence physiographic development. Lineaments were thus believed to have had an important influence upon the orography of the earth as a whole.

During this period Harder⁴⁾ worked on the relation of the drainage system of southeastern Wisconsin to the joint system of the region. Several writers had pointed out that some relationship must exist, but Harder found by actual measurement that a joint system was general throughout the area and that the drainage lines to a large extent followed the dominant directions. He also measured a small number of joint intervals and showed the existence of a tendency towards an interval of about five feet, nine feet, or eighteen feet, the two latter being roughly multiples of the first.

¹⁾ Hobbs, W. H., The River Systems of Connecticut. Jour. Geol. IX, 1901, pp. 469—485.

²⁾ Iddings, J. P., Jour. Geol. XII, 1904, pp. 94—105.

³⁾ Hobbs, W. H., Lineaments of the Atlantic Border Region. Bull. Geol. Soc. Am. XV, pp. 483—506.

⁴⁾ Harder, E. C., The Joint System of Southeastern Wisconsin, etc. Bull. Univ. of Wis. No. 138, 1906.

Harder's work was cited as an example of drainage control by joints in a paper by Hobbs¹⁾ in which he pointed out the striking relationship of the orientation of the drainage lines about the Finger Lakes of central New York to the joint directions as measured by Brown²⁾. The same author has also gathered observations for North America³⁾ and the correlation shows a very noticeable system composed of a persistent N-S, E-W set and a diagonal set which is less persistent to the 45° position. In the later paper he noted the space units as shown by the notched profiles in Norway, each notch representing a fracture which frost action had widened. The profiles show quite remarkable subdivisions into nearly equal spaces which, in turn, are divided into smaller space units. The result of this regular subdivision is a succession of repeating patterns which are rectangular in shape and are found especially in regions of low precipitation where structure exercises a large measure of control. The repetition of patterns does not go on indefinitely but one pattern gives way with remarkable abruptness to another of slightly different character. These patterns may be obscured by folds, but they may be detected by a study of the relation of stream courses to joint directions.

In Europe Professor Salomon and his students have been working on the relation of drainage to fractures and have been able to show a decided agreement⁴⁾.

Lind⁵⁾ has shown that the work of the waves in the Scilly Islands is determined by the rectangular fissures present in the rocks and not by the difference in hardness of the rock, giving the shore line the angular and indented character to be expected from such control.

¹⁾ Hobbs, W. H., Examples of Joint-Controlled Drainage. Jour. Geol. XIII, 1905, pp. 363—374.

²⁾ Brown, C. G., Unpublished data.

³⁾ Hobbs, W. H., Bull. Wis. Acad. Sci. XV, 1905, pp. 15—29; Bull. Geol. Soc. Am. XXII, 1911, pp. 123—176.

⁴⁾ Salomon, W., Die Adamellogruppe. Abh. der k. k. Geol. Reichsanst., XXI, 1908, Teil 1, S. 1—26; Die Bedeutung der Messung und Kartierung von gemeinen Klüften usw. Zeitschr. d. deutsch. Geol. Ges. LXIII, 1911, S. 496—521.

Lind, J. G., Verh. des Naturhist.-Medizin. Vereins, Heidelberg, XI, 1910, S. 7—43.

Dinu, J. J., Geologische Untersuchungen der Beziehungen zwischen den Gesteinsspalten usw. Heidelberg, 1912.

⁵⁾ Lind, J. G., Die Scilly-Inseln. Mitt. d. Geogr. Ges. in München. VI, Teil 4, S. 386—423.

Author's Investigations.

Localities Studied.

The observations discussed below were made in two localities; Schoharie County, N. Y., and the region about Cayuga and Seneca lakes in central New York. The readings for the Schoharie region were confined to the massive beds of the Coeymans limestone exposed in quarries at Howe's Cave and near Barnersville (Pl. Ia). The rocks lie horizontally and the Coeymans formation is described by Grabau¹) as a very hard, compact, rather coarse crystalline limestone of uniform grain. The upper beds are generally thinly bedded while the lower are massive. The joint system is extremely simple, consisting of one set of two parallel series running N 28° E and N 80° W. The joints stand nearly vertical and preserve a remarkable rectilinearity for long distances. A great amount of solution has taken place, as shown by the numerous caves in the vicinity, and this has served to widen the joints and roughen the surfaces. The joints are of several orders of magnitude, some cutting only part way through the Coeymans and others extending through all the formations exposed.

The measurements within the Cayuga-Seneca district were obtained from the cliffs on both sides of the lakes and from the beds of streams (Fig. 2). The rocks are bent into a series of very low folds, whose axes run nearly east and west, with dips usually under 5°. They are of Upper Devonian age and include the formations from the Ludlowville through the Portage²). Of these all but the Tully and the Tichenor are shales with interbedded sandstone and limestone layers. The general character of the shales is monotonous and, although slight differences mark the successive horizons, the lithologic changes are so gradual and so variable in horizontal distribution that it was found necessary to rely on the fossils to determine the different horizons³).

¹) Grabau, A. W., N. Y. State Mus. Bull. 92, 1906, pp. 134—135.

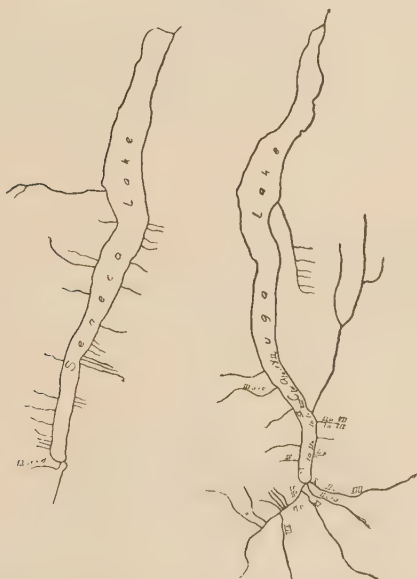
²) Folio 169, U. S. G. S. See also Luther, D. D., N. Y. State Mus. Bull. 137, 1910.

³) Folio 169, U. S. G. S.

The Tichenor or Encrinal is a stratum of hard, bluish gray limestone of about one foot in thickness, and the Tully is composed of several layers of fine grained, compact limestone which is very hard when fresh but readily weathers into small angular fragments¹⁾.

The graphic illustrations of Hall and Dana have made the joints along the cliffs of the east side of Cayuga lake famous. Here are

Fig. 2.



Map of Cayuga-Seneca region. Drainage incompletely shown. The numerals and letters refer to curves of figures 6 and 8.

to be found examples of almost perfect joint planes cutting the rocks into rectangular prisms which stand out in bold relief. The joints of this region have been studied by Brown²⁾ and Sheldon³⁾. The former made 1004 observations of joint strike and the latter over 3000 readings of both joint strike and joint dip. The dip of the

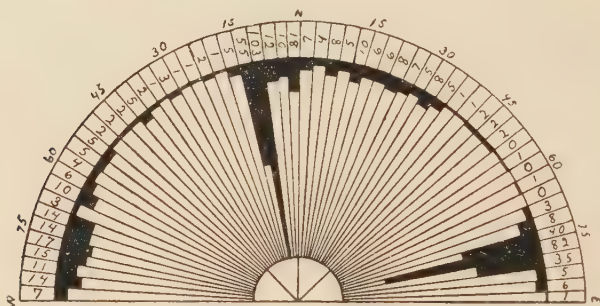
¹⁾ Luther, D. D., N. Y. State Mus. Bull. 137.

²⁾ Brown, C. G., Unpublished data.

³⁾ Sheldon, Pearl, Jour. Geol. XX, 1912, pp. 53—183.

joints is variable though it deviates little from verticality. The strikes run in all directions, but there is a noticeably predominant set com-

Fig. 3.

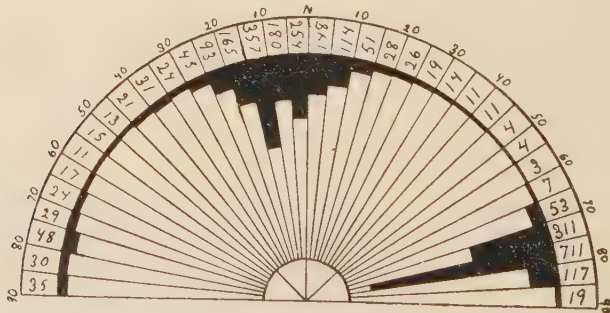


Tabulation of the strikes of the Fall Creek joint planes (after Sheldon).

posed of a $N 77^{\circ} E$ series and another which varies from 5° to 20° north of east. (Figs. 3 and 4.)

The joint planes are remarkably smooth and plane within the shale but have a gently serpentine character in the Tully limestone

Fig. 4.



Tabulation of the strikes of the joint planes of the Ithaca region (after Sheldon).

(Fig. 5). The number of joints varies, being greater in the shales than in the harder rocks, and in local areas one series may be entirely absent, although numerous joints of another series are present, e.g., on the west side of Cayuga lake a short distance north of the lower end.

Effect of the Nature of the Rock on the Character of Jointing.

The variable perfection of jointing in the different rocks was especially noticeable in the case of the Tully limestone. The inferior development in the Tully is shown by a comparison of fig. 5 and plate Ia. Harkness¹⁾ considered that the mineral nature of the rock was related to the perfection of jointing, but it seems as though the tendency of compact limestone like the Tully to break with conchoidal fracture plays some part.

Sheldon has recently noted a difference in direction of joints in the Tully as compared to the rocks above and below, but does not describe the nature of the change. A view of a rock exposure along the road leading north on the west side of the lake a short distance from the Lehigh Railroad station at Ithaca is reproduced in plate Ib. It is seen that the joints of the upper layers which are faced by a well developed joint plane are different both in number and direction from those in the layers immediately below them. This observation is similar to that of Woodworth²⁾ of cross joints in the joint fringe, though it differs in that the joints in the lower layers are not limited to the junction of the two sets of layers

and are apparently a part of the joint system of the rocks as a whole. It is apparent that, if the joints in both layers were not formed simultaneously, those of the lower layer were later, since they penetrate the upper layers for a short distance. In that case the large joint which forms the face of the upper layers should extend down into the lower layers and cut the joints of the lower layers at an acute angle. This is not the case and the joints must have been formed simultaneously. They were, therefore, subject to the

Fig. 5.



Detail of joints in the Tully limestone
(after Brown).

¹⁾ Harkness, Robert, Q. J. G. S. XV, 1859, pp. 86—104.

²⁾ Woodworth, J. B., Proc. Boston Soc. Nat. Hist. XXVII, 1896—1897, pp. 169—172.

same forces and conditions, and we are led to reject Crosby's idea that the pre-existing strain determines the direction of jointing, in favor of Becker's idea that the elasticity of the rock determines the angle of fracture, and to some extent the direction of the joints.

Influence of Joints on Topography.

Rock structures have a controlling influence on topography in regions where a mantle of soil with its vegetal covering is absent. In such regions, the physical or disintegrating agents of weathering are predominant and the transporting agents remove the material as soon as weathered, leaving the rock bare. In hot arid regions the abrasive power of the wind and changes in temperature are important, while in cold regions frost action greatly predominates. Differences in hardness of the rocks as well as structures are discovered by the wind and changes in temperature are largely independent of rock structures, but frost action is dependent on the openings in rocks which in turn are widened and become lines of least resistance for erosion by running water. Thus the influence of fractures is more important in high latitudes, although present in low latitudes.

In humid regions where the rock is often covered with a thick mantle of soil the influence of rock structures is forced into the background and slope may become the important factor in determining the nature of the drainage network. Yet the thickness of the soil varies, and streams may find the rock in the process of downward cutting and especially where faulting has occurred. Structures may thus have an influence the importance of which is yet to be determined. It is readily seen that, if we consider a stream as gradually investing a flat upland by headward erosion, the rock fractures may have a major influence on the drainage network and, in accordance with Gilbert's law of constancy of stream channels, this influence will hold at least until the stream reaches grade. Many examples of backward extension along joints are to be found in the waterfalls of the Ithaca-Seneca region.

All streams, however, do not develop by headward erosion into a flat upland but are consequent upon a slope. In such cases the channels are fixed in the mantle of soil and these courses are held as the stream cuts downward. When rock is encountered the structures can exert a minor influence only, which consists in guiding the development of tributaries to some extent and in giving a zig-zag character to the stream, which in some cases may develop into forms

resembling incised meanders, as in Coy Glen a few miles south of Ithaca, N. Y. The relative lengths of the zig-zags will depend on the relation of the initial slope to the joint directions and on the perfection of the joint system. In the Ithaca-Seneca region where the predominant joints consist of a rectangular set, the series of which are of almost equal importance, the slopes as a rule dip in a direction which makes a small angle with the $N 77^{\circ} E$ joints, and the result is a succession of zig-zags one side of which is much longer than the other¹). Examples of this are abundant and a very striking one is reproduced in plate IIa (see also figs. 10 and 11).

It is difficult to understand how fractures can exert more than a minor influence on the control of streams in a humid climate because there exists at present a mantle of weathered rock in which the stream courses become fixed, and indeed many geologists are unwilling to consider that fractures have any influence whatsoever. In considering the relative importance of fracture control, it is suggested that fluctuations in climate may have been an important factor in the case of older streams. Huntington²) has shown a pulsatory character for climatic changes which are registered so clearly in deserts, and we have evidence from the Pleistocene glaciation of pulsations of at least three orders of magnitude. Changes in climate, as shown by the Pleistocene glaciation, have occurred during the life of existing streams which were sufficient to give the regions covered by the ice sheets a climate similar to that of Norway where the structural control has been clearly demonstrated, and the duration of such climate was long enough to allow the development of fixed streams. There is a possibility, then, that the older streams in certain regions may have developed and become fixed under climatic conditions more favorable to structural control than those existing at present, and it, therefore, seems reasonable that the study of the older streams in regions where great climatic changes have occurred, especially in glaciated regions, will be profitable in helping to solve the question of the relative importance of fracture control on the relief of the land.

Spacing.

As noted in the Historical Résumé, the work of Austen, King, Harkness, Daubrée, Crosby, Hobbs, and Harder has shown

1) Tarr, R. S., Bull. Am. Geog. Soc. XXXVII, 1905, pp. 193—212.

2) Huntington, Ellsworth, The Pulse of Asia. New York and Boston, 1907.

the tendency of joints to be spaced with some regularity. That the space interval is inclined towards equality was shown for local areas by the measurements of Daubrée and Crosby. Harder has shown from a few observations a tendency towards multiple spacing of joints and Hobbs had demonstrated the same thing for the faults of the Pomperaug Valley.

The object of this investigation was to determine whether a comprehensive series of measurements of the space intervals of joints would show the same relationship. In order to do this it was necessary to select regions where the joint systems were simple and the jointing showed as perfect development as possible. The measurements include the intervals between joints which are parallel and in the same kind of rock. The readings were taken in the cliffs along the lake shores, in quarries, and on stream beds; and were measured along the faces of the joints of the perpendicular intersecting series in the cliffs and quarries, and at approximately right angles to the joint direction in the stream beds. It was impossible to differentiate between more than two orders of magnitude, therefore only well developed joints were used, except in a few cases where details were desired.

The joints selected in the cliffs were those which stand open and extend through all layers to the limit of observation. The horizontal extent could not be determined, but the joints of the intersecting series of the same order of magnitude extend for long distances. Frequent checks were made with the compass to insure parallelism. In the beds of streams the uncertain factor was the depth, but the gapping, direction, and extent were more easily determined than in the cliffs. In all cases the intervals were taken in series until further measurement was impossible, due either to the absence of joints or to difficulties of observation, generally the latter. Breaks occur in the readings, but in all series of readings all the intervals were taken in order, and it is felt that a number of such complete series, while not including all the spaces, are representative of the region. The localities are shown on the accompanying map, fig. 2. In all 2183 observations were made, most of which were about Cayuga lake and neighboring streams, since the joints of this region are better developed and more accessible than those about Seneca lake and in Schoharie County.

Several methods of assembling the data were tried and the one used was selected because of its simplicity and freedom from bias

due to the personal equation. It consists of drawing curves by means of coördinate paper of which the abscissae are the lengths of the intervals in feet, unless otherwise stated, and the ordinates are the number of joint spaces. Each abscissa includes intervals whose length falls between the limiting lines, e.g., under the tenth space were placed all intervals between nine and ten feet, or the same number of inches according to the scale used. The curves show the maximum, minimum, and most common interval, thus allowing a comparison of the intimacy of jointing in various kinds of rock, and any tendency towards spacing, either equal or multiple, since the latter would cause high points of regular recurrence in the curves. As stated above, the different orders of magnitude could not be determined, but that should not affect the character of the curves, for, if the joints are spaced regularly, the same relationships should hold for joints of all orders.

Discussion of Curves.

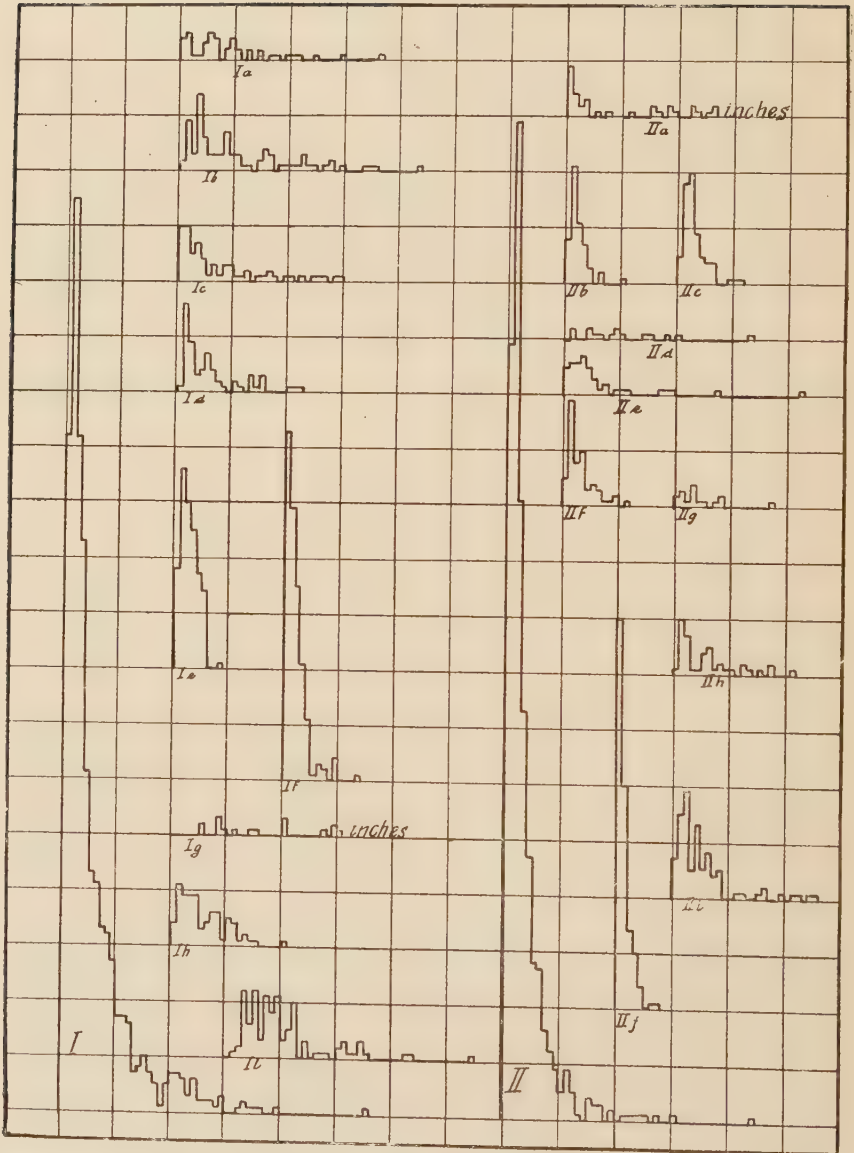
In fig. 6 are plotted the curves of the joint intervals in the shale and flagstones of the Cayuga-Seneca lake region for the series running N 77° E and N 5°—10° W. The large curves I and II include all the readings of joint intervals for these series in shale, and the smaller curves refer to local areas, although the latter are not complete.

Curve I shows a minimum of less than one foot, a maximum of 55 feet, and the most frequent interval between 1 and 2 feet. The smaller lengths greatly predominate, and there is a tendency towards a grouping of the intervals at 15—16, 20—22, 24—25 and 29—30 or, in other words, a recurrence of groups at approximately every 4—5 feet beyond the 15 foot mark.

Curve II shows the same values for the minimum and most common interval, but the maximum is at 44—45 feet and the grouping appears at 11—12, 15—16 and 19—20, the recurrence being similar to that of curve I except that it is represented earlier in the curve.

A comparison of the curves shows that the spacing of the joints of the two series is very similar. The most common interval is between 1 and 2 feet in both cases, and other frequent intervals are noted which increase in steps of approximately 4 feet and are therefore roughly multiples of what may be called the unit or most common interval. The greater maximum and the appearance of the

Fig. 6.



Graphic tabulation of the joint intervals in shale and flagstone of the Cayuga-Seneca lake region for the series which trend $N 77^{\circ} E$ (curve *I*) and $N 5^{\circ}-10^{\circ} W$ (curve *II*). The curves *Ia*—*Ii* and *IIa*—*IIj* refer to special measured profiles within the two series respectively.

groups later in the curve indicate a slight tendency for the intervals of the N 77° E series to be somewhat larger than those of the N 5°—10° W series.

The local curves may be roughly grouped into two classes; one in which a single high point in the curves is reached by gradations on one or both sides (see curves Ie, f, IIb, c, and j), and the other in which the curves show several high points of more nearly equal values, giving a more even crest line than that of the curves in the first class (see curves in fig. 6 not included in the group above and especially Ia, g, and IIa, d and g). The decided peaks in the curves of the first group may be due either to the fact that there is actually

Fig. 7.

Table 1.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23-24	25	26	27	28	
Ia																													
Ib																													
Ic																													
Id																													
Ih																													
Ii																													

Table 2.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
IIb																								
IId																								
IIe																								
IIf																								
Ilg																								
IIh																								
IIi																								

Tabulation of groups of joints in the subsidiary curves of fig. 6.

a gradation of the intervals to and from a most common interval, or that the unit of one foot used in plotting is too large to show the true relationships. That the latter is the more important is seen by the curves under IIa (in which both the foot and inch units were used) and in Ig.

In the second class, which includes about 75 % of the curves, the high points are distributed as shown in fig. 7. From these tables it is seen that in all but three cases the 1—2 foot interval is present. In table 1 there is a very marked recurrence of high points in the curves for every 2 feet up to 8 feet, and this continues to twelve feet, although somewhat less striking. Table 2 of fig. 7 shows a similar recurrence, although not so marked as in 1, up to 6 feet, at which point it fails, but reappears at 9—10 and 11—12 feet.

A consideration of curves Ig and IIa, (curve on right, in which the unit for plotting was one inch), shows peaks at 5—6, 8—9, 20—21 and 29—30 in Ig, and at 1—2, 5—6, 8—9, 12—13, and

16—17 in IIa. There seems to be little symmetry to curve Ig; IIa shows a regular recurrence of high points of almost equal values at intervals of four inches, with the exception of the third group where it falls to three inches.

In fig. 8, curves III and IV represent the intervals of joints of other directions than those in fig. 6 in shale of varying hardness. Curves III and IIIa and b represent the N 18° W series of joints measured in Taughannock gorge; III and IIIa being in very soft shales and IIIb in a hard layer of the same rocks. Curve III shows high points at 1—2, 4—5, 10—11, 12—13, 15—16, 18—19, 21—22, 29—30, 31—32, 36—37, 38—39 and 42—43 inches. The regularity is not marked in this case, but differences of 3 or 6 inches in average lengths of intervals are in the majority. In IIIa the peaks are at 4—5, 8—9, 12—13, 15—16, 18—19 and 21—22 inches and show a tendency to reappear at intervals of 3—4 inches. IIIb is in harder rock with high points at 3—4, 10—11, 15—17, 18—19, and shows little symmetry, unless it be the regression by two of the distances between the groups as their intervals increase in length.

Curve IV is of the joint intervals in shale of a series running N 14° W and shows peaks at 1—2, 8—9 and 14—15. The distance between these peaks is 6 and 7 feet, making an approximately regular recurrence.

A general consideration of the curves of fig. 6 and the upper half of fig. 8 shows that the joint intervals of the two main series, although varying somewhat widely for local areas, are very similar. The unit interval of each of the two main intersecting series is between one and two feet. The larger curves, I and II, show a tendency towards a grouping of the longer intervals at values which are approximately multiples of four feet, while the smaller curves show the same tendency for the shorter intervals, obscured in the general curves, but these are multiples of two instead of four feet. In both cases the values are multiples of the unit interval, and we may conclude that the joint intervals for shale in the Cayuga-Seneca district are most commonly from one to two feet in length and that the longer intervals have a tendency to fall into groups whose average lengths are approximately multiples of the unit interval, or, in other words, that there is a tendency for the majority of the intervals to approach equality and for the longer intervals to be multiples of the unit.

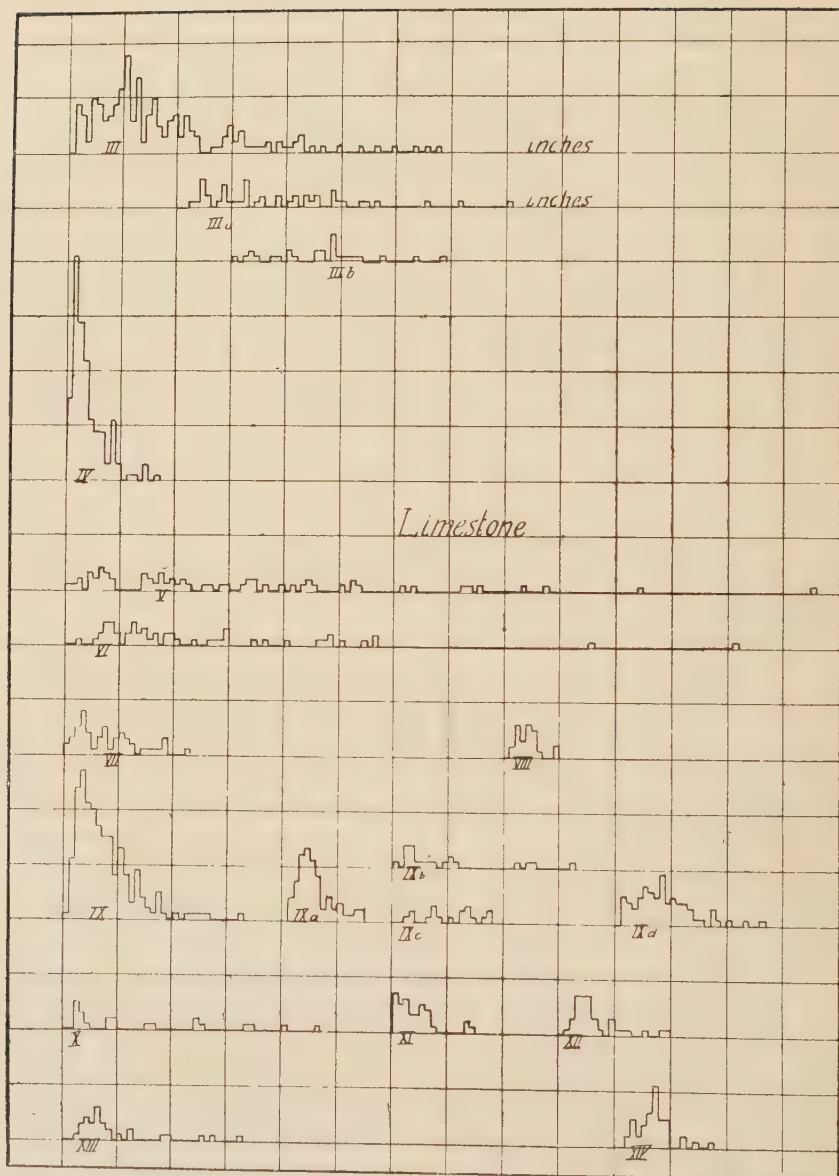
Curves for Limestone.

The curves for limestone are given on the lower half of fig. 8 and will be discussed in order. Curves V and VI are for the joint intervals from the Schoharie County area where the system is composed of series running N 28° E and N 80° W. V shows a minimum of 1 foot and a maximum of 135 feet, and VI a minimum of 3—4 feet and a maximum of 122 feet. The grouping is not well defined but occurs roughly as follows: V 3—4, 6—7, 14—15, 17—18, 33—35, 44—45, 53—54, 63, 74, 83—84, and 135—136; and for VI 3—4, 7—9, 12—13, 14—15, 19, 23—24, 29—30, 35, 40—41, 48—49, and 56—57. The regular recurrence of groups is obscure and the curves show opposite characters in many places. The unit interval is not clearly defined but may be approximated at 6—7 feet for V and 8 feet for VI.

These curves are markedly different from those for shale discussed above. There are no decided high points, the maximum and minimum intervals are much more widely separated, the grouping is less regular, and the unit interval is longer and has different lengths in the two series.

The remaining curves, with the exception of IX, a, b, c, and d, are of intervals found in hard layers interbedded in the shales of the Cayuga region, and so represent local conditions. Curve VII represents such a hard layer in the shale at Portland Point glen on the east side of Cayuga lake. The minimum interval is less than one foot in length, the maximum 24 feet, and the groups are well defined, occurring at 3—4, 7—8, 10—11, and 18—19. The groups occur at approximate multiples of 3—4 feet. Curve VIII represents a few hap-hazard joint intervals in the Tully limestone of joints running N 10—12° W. As a rule, the joints in this rock are not well enough developed to allow good measurements, and the outcrops are largely inaccessible, but a few were taken and the curve is included, although of small importance. It is a compact curve showing well defined groups at 2—3, 4—5, and 9—10 feet which show the progression 0, 2 ft. 6 in., 4 ft. 6 in., 9 ft. 6 in., and a multiple relation as well. Curves IX, a, b, c, and d show the interval relations for the joints measured in Watkins glen on Seneca lake. IX is the curve of all the measurements taken in the harder layers. The unit interval is well shown at 3—4 feet with groups at 10—11, 13—14, and 17—18. The distances between the groups, 7, 3, and 4 feet

Fig. 8.



Graphic tabulation of intervals of joints in shale, flagstone and limestone. III, N 18° W series in shale; IV, N 14° W series in shale; V—XIV, different series in limestone.

respectively, are roughly multiples of the unit interval, 3—4 feet. The groups of the subsidiary curves IXa, b, c, and d are as follows: a, obscure; b, 2—4, 10—11, 24, 33; c, 3—4, 7—8, 13—14, 17—18; d, 1—2, 5—6, 8—9, and 16—17. A rough multiple relationship is present in c and d but of different values for each, that of c corresponding to that of the general curve of the district.

Curve X of the N-S joint intervals in Fall Creek near the falls at Ithaca is the most symmetrical of all the curves plotted, and the multiple relations are so well brought out that the figures are given, arranged in groups.

Symbol (') indicates feet; (") inches

	3'	5'	9' 6"	16' 6"	25'	35'	40' 6"	46' 6"
	3'		8' 9"	15' 6"	25'	34'		
	3' 5"		9'		25'			
	3' 6"		9' 3"					
	3'							
	3' 3"							
Average . . .	3' 2"	5'	9' 2"	16'	25'	34' 6"	40' 6"	46' 6"
Nearest multiple		6' 4"	9' 6"	15' 10"	25' 4"	34' 10"	41' 2"	47' 6"
Variation . . .	0	— 1' 4"	— 0' 4"	+ 0' 2"	— 0' 4"	— 0' 4"	— 0' 8"	— 1' 0"

It is seen that out of twenty readings only one, 5 feet, need be excluded. This does not vary from a multiple much more than the 46' 6" reading but it should be kept in mind that the variation in the higher multiples must be distributed over a larger number of unit distances and is therefore much less significant. The remarkable relationship shown by the table above is nearly as well illustrated by the following short series of measurements arranged in the same way:

	6' 10"	11' 6"	18'	24'
	6'	12'	18' 6"	
Average	6' 5"	11' 9"	18' 3"	24'

The groups for curves XI—XIV, local outcrops of limestone layers in the shale of the Cayuga region, are spaced as shown in fig. 9. Of these, curve XIII shows a reappearance of groups at a 6 foot interval, and curve XIV a tendency towards a 4 foot interval.

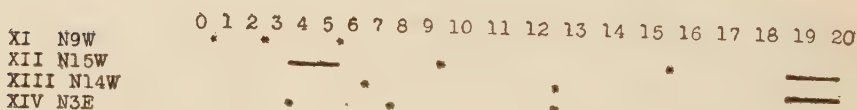
Of the curves for limestone, VII, VIII, IX, IXc, IXd, X, XIII, and XIV show a tendency towards a regular recurrence of the groups, and, in some cases, as X, the variation from a multiple of the unit is remarkably small. The only case of an intersecting

set, curves V and VI, shows a difference in the spacing for the two series.

In comparison with the intervals in shale, those in limestone are larger and show less tendency for the unit to be the greatly predominant interval. They are more variable, and the groups when present are of more nearly equal values. The tendency towards groups which appears in the curves at intervals that are multiples of the unit interval is not so prevalent, but the best examples of this were found in limestone.

With regard to the values of the intersecting series, it appears as though there is more regularity in the shales, since in the series measured the unit and the interval between the groups have the same values for both series, while in the limestone the unit is not the same for both series and the grouping is obscure. It is true that

Fig. 9.



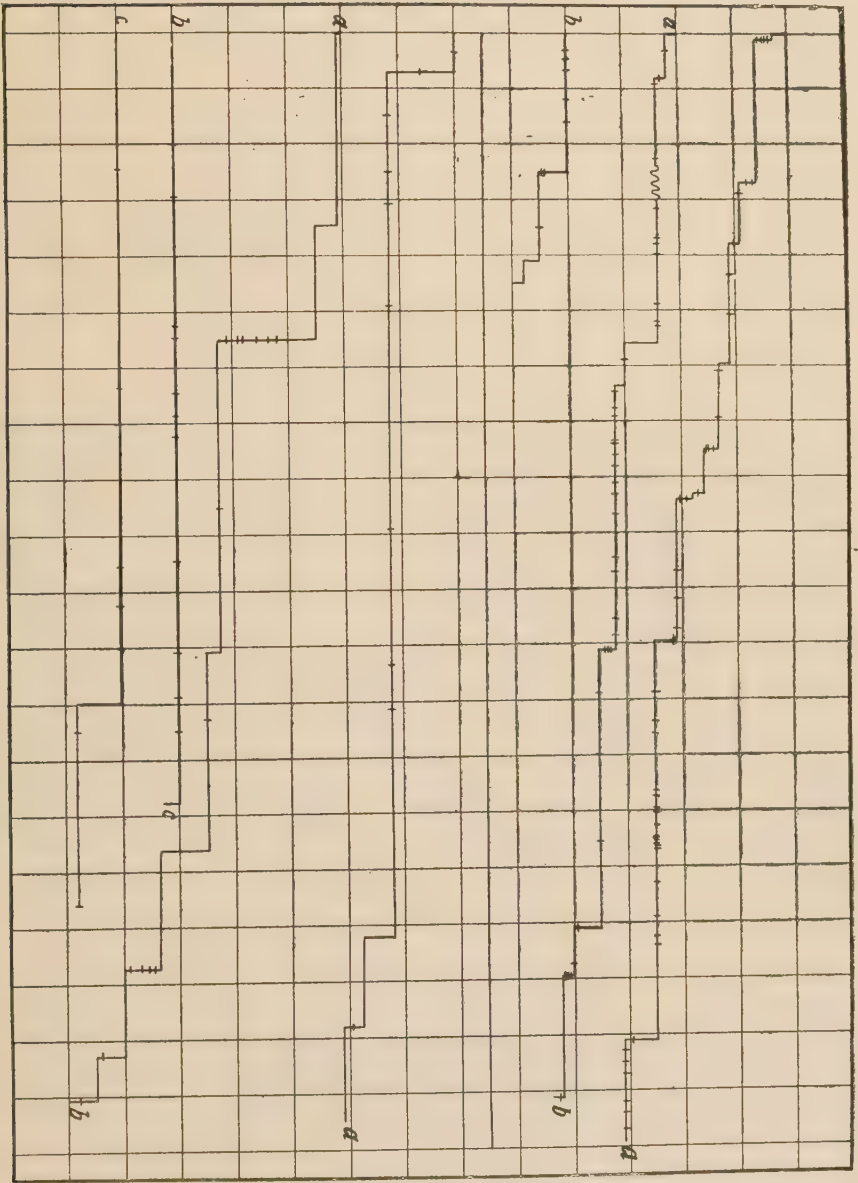
Tabulation of groups in curves XI—XIV. The heavy lines represent groups which have no decided high points, the lengths indicating the range of the intervals.

the number of observations is much smaller for the limestone series, and this fact as well as the almost exact grouping shown by the Fall Creek curve (X) increases the belief that a greater number of readings would show a better defined grouping.

Corroborative Evidence.

Photographic Study. While working in the central Illinois district, the writer considered the possibility of using photographic methods in the study of joint intervals, but the results were not satisfactory for the reason that there must always be an uncertainty as to the parallelism of the joints, especially where exposed in a cliff. The view shown in plate IIb, a photograph of a cliff in Spitzbergen, attracted the writer's attention so strongly that, although there is the uncertainty concerning the parallelism of the joints so clearly seen in the prominent stratum just above the talus slopes, measurements

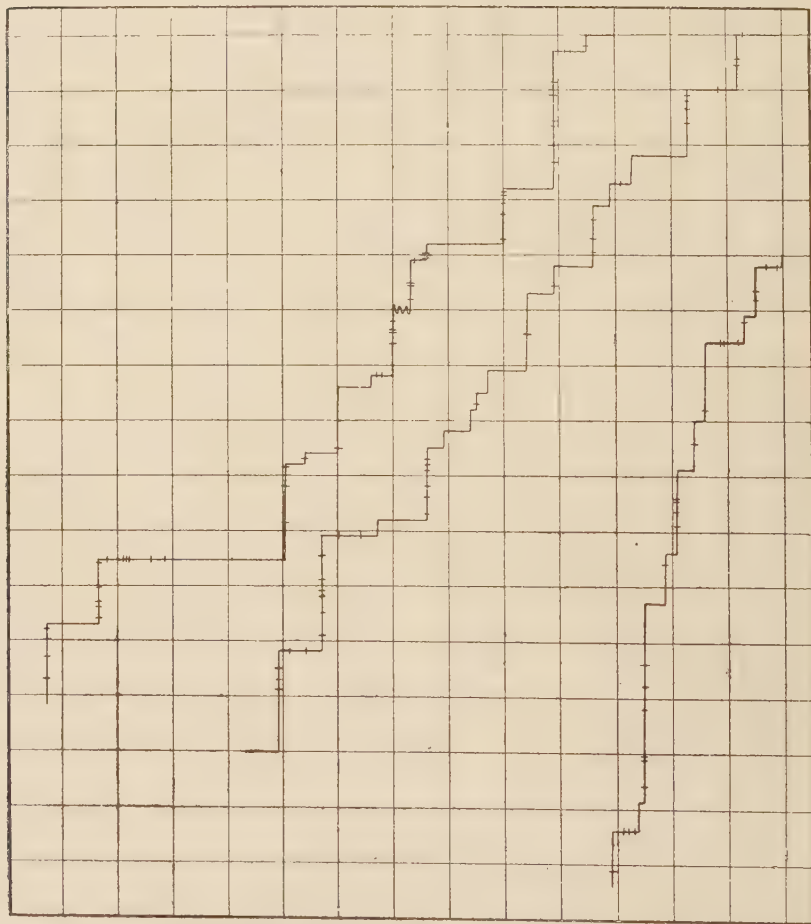
Fig. 10.



Zig-zags of cliffs along the east shore of Cayuga lake formed by wave action.
The long sides represent the faces of joints running N 5—10° W.

were made on the intervals. The results were so closely in harmony with those of the districts measured that they are added as corroborative evidence.

Fig. 11.



Zig-zags of joint faces along Paines Creek. The joint directions are $N 77^{\circ} E$ and $N 5-10^{\circ} W$. The relative lengths of the sides are approximately equal.

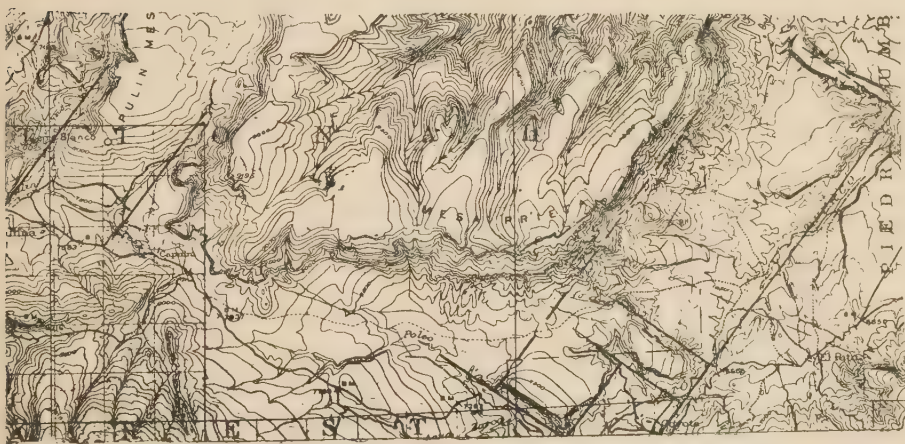
The method was to trace the joint planes on tracing paper, thus avoiding taking advantage of the width of the joint planes in the measurement. This gave a series of parallel vertical lines between which was measured by means of dividers and a scale grad-

uated to 60ths of an inch. Ten joint planes are available for measurement and the readings obtained are as follows:

27	35	(39) 41	47
	34	42	47
	34		48
Average 27	$34\frac{2}{3}$	$41\frac{1}{2}$	$47\frac{2}{3}$

It is seen that a grouping is possible which includes all but one of the readings and that the individual variations from the averages are slight. The striking thing is that the groups are separated by an interval of about $\frac{7}{60}$ ths of an inch and that they all approximate closely to multiples of this interval.

Fig. 12.



Map of a portion of the Gallina region, New Mexico, to show spacing of faults within a rectangular set. (U. S. G. S.)

Map Study. Another method of studying the problem of spacing is to use maps on which are plotted the known faults. Numerous interesting maps could be selected whose drainage network shows the peculiar control exerted by fractures, but they have been excluded because of the uncertainty in the minds of many workers as to the efficacy of fractures as a controlling influence on topographic forms. The map reproduced in fig. 12 is a portion of the Gallina, New Mexico quadrangle, a region whose present climate is favorable to structural control and whose drainage network possesses the characteristics of a region influenced by fractures, and on this map the

faults as determined by Case¹⁾ are drawn. The full lines represent observed faults and the broken lines probable faults, one a continuation of a fault observed in the Arroyo Seco and the other a probable fault in the straight narrow gorge of the Chama river. The faulting is incompletely mapped, since it was not given special attention, though the most apparent faults were noted, and a careful study would undoubtedly show many more²⁾.

The faults are in NW and NE series and intersect at nearly right angles. The multiple spacing is well brought out in the NW series. If the interval between the two faults located a short distance northeast of Coyote is taken as the unit, the intervals on either side are multiples of this, the one to the southwest being almost exactly twice, and that to the northeast slightly less than seven times the unit. The NE series does not show this clearly, but the almost square block, bounded on two sides and part of a third by cliffs, to the northeast of Aqua Zarca is an indication that the spacing is present in this series but with a slightly smaller value for the unit.

Conclusions.

From the above discussion, which has been limited to stratified rocks, it is concluded that:

1. The joint intervals in stratified rocks, as measured, vary in the same rock and in different kinds of rocks.
2. The interval in shale is less than in limestone.
3. There is a tendency towards an approximately equal spacing as shown by the presence of a predominant or unit interval, especially marked in shale.
4. There is further a tendency for the intervals greater than the unit to be of lengths which are roughly multiples of the unit interval, or, in other words, there is a tendency towards multiple spacing. The multiple spacing varies somewhat for local areas, due probably to differences in the nature of the rock, but nevertheless it is present over large areas like the Cayuga-Seneca region.

¹⁾ Case, E. C., Rept. Mich. Acad. Sci. 1912. Data obtained in advance of publication.

²⁾ Personal communication.

5. As regards the comparison of the intervals of each of two series intersecting at nearly right angles, the results are not decisive, but the unit interval and the character of the multiple spacing for shale in the Cayuga-Seneca region is the same for both series. In limestone the results are not conclusive, but it is felt that greater weight should be given to the results in shale since the number of readings is far greater than in limestone.
6. The direction of joints varies in different kinds of rock subjected to the same stresses, and the variation is due to differences in elasticity rather than to pre-existing stresses.

Explanation of Plates.

Plate I.

- a. View of joints in limestone, Schoharie County, N. Y.
- b. View of joints at contact of limestone layer exposed on west side of Cayuga Lake, N. Y.

Plate II.

- a. View of a stream controlled by joints, Cayuga Lake, N. Y.
- b. Joints exposed in a cliff at Gips Bay, Spitzbergen.

A. Joints in limestone, Schoharie County, New York.



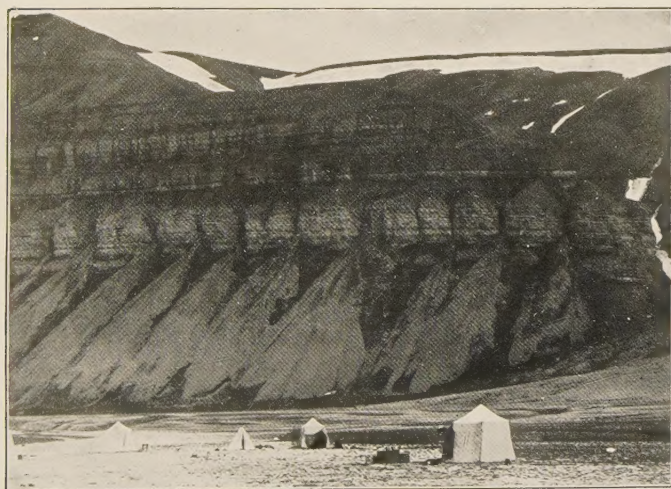
B. Joints at contact of limestone layer on west side of Cayuga Lake, N. Y.



A. Stream controlled by joints, Cayuga Lake, N. Y.



B. Joints at Gips Bay, Spitzbergen.



(Reduced from Photograph by Oscar Halldin.)

